Ion Beam Cooling by Radiation and Electron Heat Sink

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Summary

The concept for transverse temperature reduction of an arbitrary species intense ion beam is investigated. In this concept a transversally hot ion beam of arbitrary species is brought into thermal contact with a cooler electron beam with a much higher line density moving at the same speed. Thermal equilibrium is established through Coulomb interaction, with the electrons acting as heat sink. The transversally cool electron beam is either initially available or obtainable by its interaction with the comoving ions through an irreversible radiative energy loss process.

For many applications, including target irradiation and inertial confinement fusion, the availability of pinched, charge and current neutralized ion beams are necessary in order to focus and to transport them through free space to target sufficiently distant. These charge and current neutralized ion beams can be called plasma beams, since the ion beams carry with them an equal number of electrons, and thus in the frame of reference moving with the beam they are simply quasi-neutral plasmas. The plasma beam is much more attractive than the pure ion beam in terms of focussing and transporting due to a couple of reasons. First, the strength of the solenoidal magnetic field required to focus the plasma beam is significantly less than the strength of the field required for the magnetic lens to focus an ion beam without the electrons[1], due to collective effects of the magnetic field on both ions and electrons. Second, the fact that the plasma beam is space charge and current neutralized excludes the possibility of space charge blow-up during free space transport, which is an inherent problem for an un-neutralized charged particle beam. Upon reaching the target, due to their small inertia, the electrons will be scattered away leaving the ion beam to penetrate the target.

However, in free space there is no focussing force available to radially confine the plasma beam. As a result the beam will spread out radially under the influence of its own transverse pressure. Therefore, it is essential to reduce the transverse ion temperature as much as possible, since the radial expansion is controlled by the ions due to their large inertia, if both ion and electron beam transverse temperatures are of the same orders.

For a proton beam, it was proposed by Budker[2] that the protons transverse temperature can be reduced by mixing the proton beam with a comoving electron beam of lower temperature. So that in the rest frame of the two beams, relaxation theory of two Maxwellian components[3] applies and the proton transverse temperature can be reduced. This effect had been demonstrated experimentally[4].

In this paper we consider the possibility of reducing the transverse temperature of an intense ion beam of arbitrary species by the use of a comoving electron beam with a much higher line density. The ion beam temperature can then be reduced either by electron radiation cooling, or by electron heat sink cooling, or a combination of both processes. The choice between these two cooling schemes depends on the physical conditions available, and we shall discuss these two schemes shortly. For a high current ion beam, the advantage is two fold: (a) it is much easier to confine (and to focus) an electron beam than an ion beam using an axial magnetic field, and (b) the large net negative current due to the excess electrons required in these processes permits the use of a new ion beam bending technique[5], which in principle can bend the beam into cyclic motion and thus substantially reduces the long physical space required.

Electron Heat Sink: When a transversally cool high current is available, the electron heat sink technique can be applied immediately. In this case, a hot ion beam of arbitrary species is brought into thermal contact with the cool electron beam moving at the same speed but with a much higher line density. So that in the frame of reference moving with the beam, the beams behave essentially as a two component Maxellian system, then the energy relaxation time τ'_{eq} in this frame is given by[3]:

$$\tau'_{eq} = \frac{A T_e^{3/2}}{3.2 \times 10^{-9}\, \lambda n_e}, \tag{1}$$

where τ'_{eq} is in seconds, A is the ion mass number, T_e and n'_e are electron temperature and density in the moving frame and are in units of eV and cm^{-3}, respectively. λ is the Coulomb logarithm.

In laboratory frame, the energy relaxation time τ_{eq} can be written as:

$$\tau_{eq} = \frac{A\gamma^2 T_e^{3/2}}{3.2 \times 10^{-9}\, \lambda n_e}, \tag{2}$$

where the γ is the relativistic factor, and the factor γ^2 in Eq. (2) is the result of the Lorentz transformation of both time τ_{eq} and electron density n_e from the moving frame to the laboratory frame. The energy relaxation time has been defined as

$$\frac{dT_i}{dt} = \frac{T_e - T_i}{\tau_{eq}} \tag{3}$$

After thermal equilibrium has been established between the ion and electron components, the two beams have the same transverse temperature T_{eq}, which is given by

$$T_{eq} = \frac{N_i T_{i0} + N_e T_{e0}}{N_i + N_e} \tag{4}$$

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where T_{i0} and T_{e0} are initial transverse temperatures, N_i and N_e are line densities of ion and electron beams, respectively. Here we have assumed the transverse temperature of the electron beam is uniform across the beam cross section, since the energy relaxation time between electron-electron is a factor of m_i/m_e faster than that between ion-electron. By replacing the electron beam at this stage with a cooler beam, we can further reduce the equilibrium temperature. So that, we eventually have $T_{eq} \simeq T_{e0}$. However, it is obvious from Eq. (4) that this condition can also be achieved with just one electron beam, provided $N_e/N_i \gg T_{i0}/T_{e0}$, i.e. the electrons are acting as a heat sink. In this case, the energy relaxation time can also be reduced, since τ_{eq} is inversely proportional to n_e as can be seen in Eq. (2).

As a numerical example, we consider the case when $n_i = n_e = 10^{12}$ cm^{-3}, ion and electron beam radius are 10 cm and 1 cm, respectively, $T_{i0} = 200$ eV, $T_{e0} = 5$ eV, $A = 1$, and $\gamma = 1.6$. Then $T_{eq} = 6.93$ eV and $\tau_{eq} \simeq 6 \times 10^{-4}$ seconds, which corresponds to a linear distance of 140 kilometers. While the linear distance required for the cooling process appears excessive, the fact that $N_e/N_e \gg 1$ allows the ion and electron beams to be bent simultaneously[5] into cyclic motions, and thus substantially reduces the physical space required.

However, this cooling technique requires an initially cool electron beam. In the case when a transversally cool electron beam is not readily available, then radiation cooling works very effectively for ion beams with moderate or high atomic number, i.e. $Z > 8$. The radiation cooling can also be used to produce a cool electron beam, necessary in the cooling (electron heat sink) of a low atomic number ion beam. As an example, in the following analysis we choose a moderate atomic number ion beam. However, the general principle described there should also be applicable to heavy ion beams.

Radiation Cooling: In this cooling scheme, a transversally warm (8 eV $< T_{e0} <$ 200 eV) high density electron beam is brought into contact with a moderate or high Z ($Z > 8$) singly charged ion beam moving at the same speed. In the frame of reference moving with the beam, the warm electrons continuously collide with ions, lose their kinetic energy, and therefore excite the ions to a higher atomic energy level. The ions eventually release this extra energy by radiation and return to the ground state. As a result, the electrons are cooled by the ions, which are then cooled with the electrons acting as a heat sink.

In the moving frame, the total power P_r radiated per unit volume is determined by[6]

$$P_r = n_e' n_i' f(Z,T_e) \quad \text{eV/cm}^3\text{-sec} \tag{5}$$

where n_e' and n_i' are electron and ion densities in the moving frame and are in unit of cm^{-3}, T_e is electron temperature in the moving frame, and f is a function of ion atomic number Z, and electron temperature T_e. For parameters Z and T_e satisfying $8 \leq Z \leq 20$ and 8 eV $< T_e <$ 200 eV, the function $f(Z,T_e)$ can be approximated as[6]

$$f(Z,T_e) \simeq 1.1 \times 10^{-13} Z^2 \; T_e + 3.6 \times 10^{-12} \frac{Z^4}{\sqrt{T_e}} + 4.1 \times 10^{-11} \frac{Z^6}{T_e^{3/2}} \tag{6}$$

For illustrative purposes, we consider the case of $Z = 20$. Then we can approximate Eq. (6) as

$$f(20,T_e) \simeq 2.6 \times 10^{-3} T_e^{-3/2}. \tag{7}$$

The energy equation in the moving frame is given by

$$\frac{dU}{dt_m} = - P_r \cdot S_i \tag{8}$$

where $U = N_e T_e + N_i T_i$ is the energy density per unit length, t_m is the time variable in the moving frame, and S_i is the ion beam cross section. For $N_e/N_i \gg 1$, Eq. (8) can be written in the laboratory frame as

$$\frac{dT_e}{dt} = - 2.6 \times 10^{-3} \frac{S_i}{S_e} \frac{n_i}{\gamma^2 T_e^{3/2}} \tag{9}$$

where S_e is the electron beam cross section, and the factor γ^2 is the result of the Lorentz transformation of both time and density from the moving frame to the laboratory frame. Integrating Eq. (9) over t, the electron transverse temperature as a function of time is finally given by

$$T_e(t) = T_{e0} \left(1 - \frac{6.6 \times 10^{-3} \, n_i t}{\gamma^2 T_{e0}^{5/2}} \frac{S_i}{S_e}\right)^{2/5} . \tag{10}$$

It should be emphasized that this cooling scheme places a lower limit of about 8 eV on electron temperature, due to quantum mechanical effects. As a result, the lowest ion transverse temperature is also limited to 8 eV.

As a numerical example, let us consider the case when $n_e = n_i = 10^{12}$ cm^{-3}, $S_i = 1$ cm^2, $S_e = 10$ cm^2, $\gamma = 1.6$ and $T_{e0} = 200$ eV. Then it takes roughly 4.3 x 10^{-3} seconds to cool the electron beam, and thus ion beam, from 200 eV to 8 eV. We note that while the fact that $N_e \gg N_i$ is itself inefficient (slows down the cooling time) in this technique, it permits us to bend the ion and electron beam simultaneously and therefore substantially reduces the physical space required for the cooling technique.

References

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